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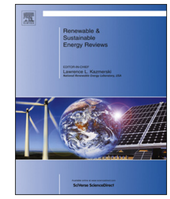

Adoption of smart grid technologies: An analysis of interactions among barriers

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ABSTRACT

Global electricity demands are increasing at rapid pace. Energy supply, their usage and technologies involved need to be more economical, environment friendly and socially sustainable. Efforts are being done all over the globe to reduce this greenhouse effect; and renewable energy technologies to combat climate changes, which require extensive changes to the current electricity generation and distribution systems. To meet this goal, it is required to optimize the grid operations and available resources to meet the ever increasing energy demands in an efficient, effective and environment sustainable way. It has been found that smart grid technologies have not been so popular due to some obstacles that are hindering its maturation and rapid deployment. An attempt has been made to identify and analyze the barriers to implement smart grid technologies adoption. Twelve relevant barriers towards implementation of smart grid technologies have been identified from extensive literature review and duly validated with experts' (from academia and industry) opinions. Also, valuable experts' opinions have been utilized to identify contextual relationships among these important barriers and a hierarchical model has been developed based on Interpretive Structural Modeling methodology. Matrice d'Impacts Croises-Multipication Applique´ an Classment (MICMAC) analysis has also been used to: classify the barriers based upon dependence and driving power; and validate developed ISM based model. “Lack of Regulatory Framework” barrier has been identified as driver or independent level barrier i.e. most important bottom level barrier hindering adoption of smart grid technologies. The developed structured model will help to understand interrelationships and interdependencies among the identified barriers to implement smart grid technologies. Different solutions for handling these identified barriers have also been suggested in the paper. Organizations involved in power generation and distribution may be benefited by understanding of these barriers, their interactions and suggested mitigation solutions towards effective adoption of smart grid technologies.

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1. Introduction

The electrical power generation and distribution using traditional grids that serve consumers today have been evolved over more than a hundred years. Current grids have served well in the past but will not be adequate in the future [1,2] in terms of their efficiency and environment friendliness. However, new challenges are arising from ever increasing consumer demands, global warming and depletion of non-renewable energy sources at much rapid rate [3,4]. Electricity grids must ensure safe, secure, uninterrupted and sustainable electricity supplies, take advantage of new technologies and integrate with large scale renewable generation systems. To meet requirement of managing intermittency of renewable energy sources intelligently to avoid future supply failures, which provide an excellent opportunity for the deployment of smart grid technologies adoption needs to be considered as an excellent opportunity [5]. As peak demand of electricity is increasing at rapid pace in all regions, smart grids deployment may also help in managing the increase in projected peak demand [6].

1.1. Drivers of smart grid

The electricity supply industry is facing lot of challenges: supply-demand gap; rising costs; low energy efficiencies; and global warming, caused by traditional electricity generation and distribution practices. Also there are many other factors which are driving the need for adoption and implementation of the smart grid technologies. Some of the key drivers of smart grid technologies are: increasing demand of electricity; supply shortfalls of electricity; need of reduction losses; peak demand management; integration of renewable energy generation systems; solution to global warming; effective use of electric vehicles; better customer satisfaction; overcoming difficulties in meter reading; poor efficiencies of conventional power generation systems; potential of technological advancements and new business opportunities [7]. A summary of these important drivers have been given below.

1.1.1. Increasing demand of electricity

Global energy demand increased may be assigned to many valid reasons: increasing world population; growing needs of products; rapid industrialization rate; high customized and digitalized services; rapid development of smart home appliances; communication systems' electricity demand; lazy lavish life style fostering automation (using electrical and electrical gadgets); increased usage of electricity driven vehicles; late hours working culture requiring appropriate illumination; and increasing demand of electricity in providing human comforts (air conditioning) [8]. As per the International Energy Agency (IEA), the global energy demand will increase by more than 50 percent till 2030 [3]. Due to lack of real-time pricing signals, peak demand is also expected to increase steadily over time [5].

1.1.2. Supply shortfalls of electricity

Supply-demand tension has taken its toll in various countries around the world over the last several years. Governments and

Table 1
Components of Smart Grid.

S. no.	Component	Description
1.	Smart generation and storage	Smart grid is capable of integrating central and distributed power generation systems and may optimize the process of electricity generation by getting feedback from multiple monitoring points in the grid. It has electrical energy storage components like batteries, flywheels or super-capacitors or plug-in hybrid electric vehicles [19].
2.	Smart distribution	Smart distribution anticipates for the failures and outages based on real-time data and outage history; and responds in a self-healing manner [19].
3.	Intelligent appliances	Smart grid may accommodate smart or intelligent appliances which are capable of deciding when to consume power based on pre-set customer preferences. This may reduce peak load demand, which has a major impact on electricity generation costs [19].
4.	Customer information interfaces and decision support tools	Smart grid has information interfaces and decision support tools which are used by customers to get the required information about electricity consumption and take the appropriate action to manage it effectively [13].
5.	Smart meters	Smart meters support two-way communications between customers and power providers, which enable automatic collection of billing data, faster detection of outage and fault location. Smart meter may read voltage, current, and power factor to support intelligent distribution system [13,19].
6.	Sensing and measurement	Smart grid technologies support data acquisition in order to evaluate the condition and integrity of the grid and also support automatic meter reading and prevent energy theft [19].
7.	Sub-station controllers	Sub-station controllers incorporate two-way communication between customer and electricity distribution system. These controllers also incorporate advanced cyber security and protection elements for safe distribution of electricity at all levels [20].
8.	Integrated communications	Integrated communications between various elements of smart grid (central and distributed generation stations, micro grids, central controllers, regional controllers and end-point users) may be made with help of wide-area networks, servers gateways etc. [13].
9.	Interoperability framework	Interoperability framework and associated standards incorporates integration of large number of power generating sources, different types of energy distribution networks and energy consumers [21]. Smart Grid enables the different systems to exchange meaningful and actionable information to establish coordination among them.
10.	Advanced control methods	Advanced control devices and algorithms are adopted to analyze and diagnose the grid conditions and autonomously. Advanced control methods are helpful to take appropriate corrective actions to eliminate, mitigate, and prevent outages and power quality disturbances [19].
11.	Electric transportation	Large number of electric vehicles charging can be accommodated by smart grid. Intelligent communications and monitoring systems can synchronize the simultaneous charging of electric vehicles in order to reduce the load on grid and distribute it over the time [22].

utilities have faced gaps between electricity supply and demand, which has led to blackouts and load shedding and translated into electricity shortfalls [9]. Electricity generation is not growing at the same pace as of increase in demand, causing shortfall of electricity supply [10].

1.1.3. Need of reduction in losses

Great losses have been observed taking place in generation, transmission, distribution and usage of electricity. These losses need to be appropriately addressed with continuously monitoring to stop the common problems like theft of electricity [11].

1.1.4. Peak demand management

Managing peak demand (which has been observed increasing rapidly over the last few decades because of many valid reasons such increasing number of consumers, affordable electrical appliances and services etc.) may be recognized as challenge of all times. In fact, peak demand mismanagement may lead to: exert extra burden on present electric grid [7]; and require higher reserve margins for unforeseeable outages.

1.1.5. Integration of renewable energy generation systems

Renewable energy technologies can reduce environmental as well as social impacts and provide low cost alternatives than conventional energy technologies for various applications [12]. It will also add to the capacity of existing system and reduce the emission of green house gases, which are responsible for global warming and ozone layer depletion [13].

1.1.6. Solution to global warming

It has been accepted globally that environmental pollution has been reached to end limits [11]. It is estimated that the United States is the source of one-fourth of the world's GHG emissions and that the electric power industry accounts for one-third of these [14]. Use of smart grid technologies may be realized as an intelligent and smart answer minimizing GHG.

1.1.7. Effective use of electric vehicles

A smart grid may accommodate electric vehicle charging and it may bring all elements of the electricity system closer together to improve overall system operation for the benefit of consumers and the environment [15]. Smart grid technologies may be utilized to generate environment friendly electricity and feed huge transportation systems like ‘Delhi Metro Railway Corporation’ network electricity demand.

1.1.8. Better customer satisfaction

Smart grids give consumers a visibility into real-time pricing and provide opportunity to minimize the total amount of their bills by smartly choosing the volume and price of consumption that best suits their needs [16].

1.1.9. Overcoming difficulties in meter reading

Smart metering may enable the meter reading nearly instantaneous and remotely [17] leading to many advantages: less time consuming; cost effective and accurate. Further, it may also lead to have better maintained customer relations by providing transparency in meter reading system.

1.1.10. Poor efficiencies of conventional power generation systems

Traditional power generation systems have been observed with poor efficiencies. Smart grid technologies may be good solution to save a reasonable quantity of fuel and greenhouse gas emissions [5].

1.1.11. Potential of technological advancements

The technological advancement in the field of computing and telecommunications may support the concept of smart grid technologies adoption as it requires lot of measurements,

monitoring, computing and communications as a network [18]. The development of the smart grid may led to realize the full potential of individual technologies (distributed solar photovoltaics (PV), electric cars, demand-side management, and large central station renewables such as wind and solar farms) supporting non conventional power generation [5].

1.1.12. New business opportunities

Smart grid technologies implementation may open those to new business opportunities in the field of manufacturing of innovative products, processes and services [7]. Manufacturing of tools, equipments, instruments and apparatus supposed to be used in smart power generation and distribution (like smart power meter); and smart appliances (electric vehicles) may be seen as good examples of business opportunities in manufacturing sector.

1.2. Components of smart grid

Although the smart grid may be defined in a number of ways, some typical components of a smart grid are summarized in Table 1 [13,19–22].

1.3. Organization of the paper

Identification of barriers to implement smart grid technologies adoption has been done in Section 2 by exploring relevant literature. Section 3 of the paper contains step wise elaborated ISM methodology to find levels of these barriers. In Section 4 follows the ISM based model formation of barriers to adopt smart grid technologies. MICMAC analysis has been presented in Section 5. Discussions of this research, proposed solutions for managing these barriers and implications of the research are presented. In the last section, conclusions are presented followed by limitations and scope for future research.

2. Barriers to smart grid Technologies adoption-identification

Today's grids are based on thermal power generation systems observed with less efficiency and emission of GHG gases, which in turn causes global warming and ozone layer depletion. These are connected to large central power stations high voltage transmission systems and supply power to medium; and low-voltage local distribution systems [1]. These conventional grids have been reported lacking in advance monitoring and controlling features. Conventional sources of energy are also depleting at very rapid pace and they are expected to vanish within few decades. In this scenario, smart grid technologies adoption becomes more important and relevant. The benefits of the smart grid are substantial; and it has the potential to reduce GHG emissions, reduce energy costs, fulfill growing needs and improve load control [2]. However, the potential advantages of smart grid technologies are very attractive, the extent of smart grid technologies adoption and actual realization of benefits is very low. Only a small portion of the companies have begun experimenting for advancement and making it practically feasible to adopt [23].

Various barriers to implement smart grid technologies adoption have been: identified from the literature review; sorted after discussions with experts; and validated by experts' opinions and brainstorming session. Literature was reviewed to identify potential barriers to smart grid technologies adoption followed by conduction of an idea engineering workshop with experts (academia and industry) to validate the identified barriers from literature review. Four experts were from academia and three experts were from industry. Brainstorming session was conducted to reach consensuses about the contextual relationships (pair wise) to form a structural self interaction matrix (explained in Section 3.1). Twelve most important relevant barriers in adaptation of smart gird technologies, resulted from above mentioned exhaustive exercise, have been briefly detailed.

2.1. Huge amount of investment and lack of financial resources

Implementation of smart grids will require additional investment and financial reserves for the smart grid technology transfer, provision of adequate infrastructure, communication systems, hiring of skilled professionals (engineering and other professionals), R&D work and integration with renewable energy sources. However, the payback period is relatively long comparing against high initial investment [24]. Although, substantial environmental and societal benefits may be achieved by implementation of smart grid technologies, government authorities may need to have sufficient proofs for justification for high investment [19]. Vendors' and original equipment manufacturers' reluctance has to be properly removed by ensuring guaranteed return (long term) to systematic payback scheme supported by incentives and subsidies provided by government authorities [25]. Also, many developed and developing nations affected by the global recession are struggling to pay for renewal of their entire major infrastructure and are facing financial challenges [26].

2.2. Market uncertainty

There are not yet specific policies and regulations for free markets tariffs [27]. The standards and business modes of smart grids have to be established towards universally accepted standardized regulatory definitions to generate revenue [29–31]. Adequate international bodies' consensus and government consensus, strong political commitment and global cooperation are lacking to organize the dynamics of energy market [1].

2.3. Lack of regulatory framework

Most of the electrical systems of world regulate electric power through policies and regulatory frameworks designed a long back ago [32]: although appropriate for those times, many of those regulations are now obsolete. Traditional regulatory systems are not harmonized and tend to discourage investment in innovative technologies like smart grid. The regulatory aspects of the smart grids are currently ambiguous [33–36]. Power utility related policies and procedures may be framed to assure compliance with legislative or regulatory requirements for smart grid technologies implementation [37].

2.4. Low public awareness and engagement

Customer requirements for the smart grid technologies are lacking due to inadequate incentives for consumers to adopt systems to manage their electricity consumption [38]. General public need to be educated and aware through properly managed awareness programs educating them about benefits of smart grid and technicalities of usage smart grid may be installed with advanced metering and two-way communication along with time-of-use rates. Reluctance of public for adoption of smart grid installations is to be carefully tackled. Consumer advocates may object to certain smart grid functionality, such as remote disconnect and new rates in the interest of protecting disadvantaged consumers [25].

2.5. Lack of innovativeness in the industry

Organizational attitudes towards innovation may be very discouraging [23]. Instead of looking for innovative solutions to the problems of societal benefits, they want to work with traditional methods for safe and guaranteed return on investment. From

a company's point of view, implementing a smart energy solution in a previously well-functioning environment may reduce reliability and evokes worries about a loss of control, if automatic switching operations are intended. Companies have fear of losing their traditional customers if they start using innovative technologies [29]. Innovation in technologies and systems like smart meters, energy controllers, communication systems have been required for improving efficiencies in the smart grids [39].

2.6. Lack of infrastructure

Additional infrastructure will be required for the deployment and operation of smart grid technologies. The smart grid may be understood as modern electric power grid infrastructure for improving efficiency and reliability through automated control, high power converters, modern communications infrastructure, sensing and metering technologies, and modern energy management techniques based on the optimization of demand, energy and network availability, and so on [17]. A well defined communication architecture, sensors, intelligent electronic devices, distributed energy resources, cyber security devices, advanced metering system and other end-use devices are key elements of smart grid which need to be added in the present electricity system [33]. Additional stand-by capacity of electricity generation might be required for the times when the intermittent renewable energy resources cease to generate power [1].

2.7. Technology immaturity

As the smart grid technology is still emerging and standards are not in place, all of its features are not yet tested and proved [32] and technology need to validate estimates of customer load with customer data [31]. The process of smart grid deployment may be slow due to technology immaturity; and non confirmation about small scale capital investments and returns on it [23]. Further, because of this immaturity of technology, ancillary facility cannot cop up with the requirements of smart grids [30].

2.8. Lack of necessary technical skills and knowledge

As we move towards achieving technology transfer process completion and further utilizing the technology, there would be continuous demand for new cadre of trained engineers and managers to bridge the gap and to develop new skills in analytics, data management and decision support [32]. The utility industries find technical competence as one barrier to the adoption of smart grid technologies and organizations may postpone or even cancel the adoption decision because of the lack of necessary technical skills and knowledge [23].

2.9. Integration of the grid with large scale renewable generation

To enhance the capacity of electricity systems and reduce their dependency on non-renewable energy sources, integration of both central and distributed generation may be identified important; and integration of the grid with large scale renewable generation requires coordination among different suppliers of energy [7]. It may also require efficiently linking the different power sources with the growing demands of consumer [1]. An important feature of smart grids is the interconnection between large number of dissimilar energy distribution networks, power generating sources and energy consumers [21] leading to many benefits: economic; environmental; social; operational etc. Proposed smart grid may be an ultra large scale system of systems where different systems need to exchange meaningful, actionable information, with common meaning and agreed types of responses to a degree which has not been used in the industry before [35]. Lack of coordination between electric energy and telecom agencies is a barrier to effective smart grid development [27].

2.10. Need of advanced bi-directional communication systems

Bi-directional flow of energy and information may be recognized as back bone of smart grid; and advanced communications technology is an essential enabling component of the future smart grid. The smart metering communications is a major component of the overall smart grid communications architecture [21]. Distribution of real time control of electricity networks among different generating points, transmission networks and end-users may be a challenging job [40]. Control systems will have to be modified and new operating procedures will need to be developed like dealing not only with the bidirectional power as well as two-way data communication system [41].

2.11. Lack of open standards

Lack of clear standards and guidelines across the grid to support system interoperability, has been identified as a barrier

Table 2
Brief summary of various barriers to smart grid technologies deployment reported in literature.

S. no.	Barriers to implement smart grid installations	Description of barriers	Researchers
1.	Huge amount of investment and lack of financial resources	Huge amount of investment is required to install smart grid. Investors are not interested to invest in smart grid installations until universal standards are adopted and return on investments is guaranteed.	[1,5,7,19,23–29]
2.	Market uncertainty	Due to lack of revenue uncertainty and sufficient market base, private investment is discouraged.	[1,27,29–31]
3.	Lack of regulatory framework	Traditional regulatory system is needed to be modified to encourage utilities to invest in the smart grid installations.	[1,5,7,23,28–37]
4.	Low public awareness and engagement	The benefits of a smart grid can be achieved only if customers are fully aware of smart grid concept and they use all of its features.	[5,7,25,29,32,35,38]
5.	Lack of innovativeness in the industry	Organizational attitudes towards innovation are not enthusiastic. They have fear of adopting newer technologies.	[1,23,29,39]
6.	Lack of infrastructure	Additional infrastructure is required to deploy smart grid technologies	[1,17,33]
7.	Technology immaturity	Smart grid technologies are still emerging and standards are to be developed and maintained.	[7,23,30–32]
8.	Lack of necessary technical skills and knowledge	There is a shortage of training and technical staff required for deploying and operating especially intra grid control applications.	[1,23,32]
9.	Integration of the grid with large scale renewable generation	Integration of innovative technologies like renewable/sustainable energy technologies and distributed generation, into existing grids is a challenging task.	[1,7,21,27,35]
10.	Need of advanced bi-directional communication system	The bi-directional communication links may be harmed by natural disasters, man-made accidents and international attempts.	[21,40,41]
11.	Lack of open standards	Many proprietary standards used today need to be replaced by open standards worldwide.	[7,29,34,35,42]
12.	Cyber security and data privacy	Smart grid communication technologies and consumer data are open to cyber attack.	[5,7,21,24,25,43,44]

to smart grid deployment [29]. Interoperability standards set for energy distribution networks, power generating sources and energy consumers, may not keep pace with smart grid installations. Many proprietary standards which are in use today are required to be replaced by open standards and open standards will help in encouraging multiple suppliers to innovate new technologies and compete with regards to features and performance [35]. The smart grid installation may become very successful following the success story of internet adopting consistent and open standards worldwide like HTML and internet protocol. In fact, open standards for smart grid installation have been observed in either introduction phase or development phase in various developing and even in developed countries. It is going to take long time in completing, stabilizing and normalizing them [42].

2.12. *Cyber security and data privacy*

Smart grid communications may play an important role in maintaining high levels of electric systems': reliability; performance and manageability. But at the same time, the grid may to subjected to attack because many of the technologies being deployed to support smart grid projects, like smart meters, sensors, and advanced communication networks, are interoperable and open [7,24]. Frequent smart metering data collection and analysis may help in improving energy efficiency and framing future policy, however this comes at the cost of user privacy [21]. Cyber systems may be vulnerable to worms, viruses, denial-of-service attacks, malware, phishing, and user errors that compromise integrity and availability [43]. Analyzing and implementing smart grid security may be a challenging task, considering the scale of the potential damages that could be caused by cyber attacks [44].

The brief summary of various barriers to smart grid deployment as reported in literature has been reported in Table 2.

3. Interpretive Structural Modeling Technique for finding the levels of barriers to implement smart grid

Interpretive Structural Modeling (ISM) technique was introduced by J. Warfield in 1974 to indentify relationship among specific items related to a problem or complex issue [45,46]. ISM is an interactive learning process in which a set of different and directly related elements is structured into a comprehensive systemic model and the advantage of the ISM methodology is that it transforms unclear and poorly articulated models of systems into visible and well-defined models [47,48]. It portrays the structure of complex issues of the problem (technical, administrative and managerial) under study, in a carefully designed pattern combining three modeling languages: words; digraphs; and discrete mathematics, to offer a methodology for structuring complex issues [49]. ISM is interpretive as judgment for imposing order and direction on the complexity of relationship among variables (barriers to adopt smart grid technologies) of a system to form a structured model [50]. The following steps, which lead to development of an ISM based model, are as follows [49–53]:

1. Identify variables to be studied under ISM methodology. Barriers to implement smart grid technologies adoption have been identified as variables in our research work. Relevant contextual relationships (pair wise) among the variables have been identified to form Structural Self-Interaction Matrix (SSIM).
2. From the SSIM an initial reachability matrix is developed by replacing symbols with binary digits (0 and 1).
3. The matrix is checked for transitivity rule to form final reachability matrix. The transitivity of the contextual relationships is a basic assumption made in ISM and it states that if variable *X* is related to variable *Y* and variable *Y* is related to variable *Z*, then variable *X* is necessarily related to variable *Z*.
4. Partitioning is carried out to find various levels of the model.
5. Interpretive Structural Model is developed by replacing variable nodes with statements in diagraph; and it is reviewed to check for conceptual inconsistency and followed by necessary modifications, if required.

3.1. *Structural Self-Interaction Matrix (SSIM)*

As mentioned earlier in Section 2, with the consultation of academia and industry experts during an idea engineering workshop conducted, the contextual relationships were identified among the barriers to smart grid technologies adoption. *V*, *A*, *X* and *O* (four symbols) have been used for developing SSIM to denote the direction of relationship between two barriers '*i*' and '*j*': *V* means that barrier '*i*' will dominate in the direction of barrier '*j*'; *A* means that barrier '*j*' will dominate in the direction of barrier '*i*'; *X* means that both barriers '*i*' and '*j*' will dominate in the direction of each other; and *O* means that the barriers '*i*' and '*j*' are not related to each other. The development of SSIM for barriers to adopt smart technologies grid using above symbols has been explained as follows:

Barrier 1 dominates to barrier 6 therefore, symbol '*V*' has been given in the cell (1, 6) of SSIM table; Barrier 11 dominates to barrier 2 so symbol '*A*' has been given in the cell (2, 11); of SSIM table; Barriers 7 and 8 dominate to each other so symbol '*X*' has been given in the cell (7, 8) of SSIM table; and in our study, all barriers are interrelated, therefore no symbol '*O*' has been given in the SSIM and so on.

Table 3
Structured Self Intersection Matrix (SSIM) for barriers to adopt Smart Grid technologies.

S. no.	Barrier to implement Smart Grid	12	11	10	9	8	7	6	5	4	3	2
1	Huge amount of investment and lack of financial resources	V	A	V	V	V	V	V	V	A	A	X
2	Market uncertainty	V	A	V	V	V	V	V	V	A	A	
3	Lack of regulatory framework	V	V	V	V	V	V	V	V	V		
4	Low public awareness and engagement	V	A	V	V	V	V	V	V			
5	Lack of innovativeness in the industry	V	A	A	A	A	A	A				
6	Lack of infrastructure	V	A	V	V	V	X					
7	Technology immaturity	V	A	V	V	X						
8	Lack of necessary technical skills and knowledge	V	A	V	X							
9	Integration of the grid with large scale renewable generation	V	A	X								
10	Need of advanced bi-directional communication system	V	A									
11	Lack of open standards	V										
12	Cyber security and data privacy											

Table 4
Initial reachability matrix for barriers to adopt Smart Grid technologies.

S. no.	Barrier to implement Smart Grid	1	2	3	4	5	6	7	8	9	10	11	12
1	Huge amount of investment and lack of financial resources	1	1	0	0	1	1	1	1	1	1	0	1
2	Market uncertainty	1	1	0	0	1	1	1	1	1	1	0	1
3	Lack of regulatory framework	1	1	1	1	1	1	1	1	1	1	1	1
4	Low public awareness and engagement	1	1	0	1	1	1	1	1	1	1	0	1
5	Lack of innovativeness in the industry	0	0	0	0	1	0	0	0	0	0	0	1
6	Lack of infrastructure	0	0	0	0	1	1	1	1	1	1	0	1
7	Technology immaturity	0	0	0	0	1	1	1	1	1	1	0	1
8	Lack of necessary technical skills and knowledge	0	0	0	0	1	0	1	1	1	1	0	1
9	Integration of the grid with large scale renewable generation	0	0	0	0	1	0	0	1	1	1	0	1
10	Need of advanced bi-directional communication system	0	0	0	0	1	0	0	0	1	1	0	1
11	Lack of open standards	1	1	0	1	1	1	1	1	1	1	1	1
12	Cyber security and data privacy	0	0	0	0	0	0	0	0	0	0	0	1

Table 5
Final reachablility matrix for barriers to adopt Smart Grid technologies.

S.no.	Barrier to implement Smart Grid	1	2	3	4	5	6	7	8	9	10	11	12	Driving Power↓
1	Huge amount of investment and lack of financial resources	1	1	0	0	1	1	1	1	1	1	0	1	09
2	Market uncertainty	1	1	0	0	1	1	1	1	1	1	0	1	09
3	Lack of regulatory framework	1	1	1	1	1	1	1	1	1	1	1	1	12
4	Low public awareness and engagement	1	1	0	1	1	1	1	1	1	1	0	1	10
5	Lack of innovativeness in the industry	0	0	0	0	1	0	0	0	0	0	0	1	02
6	Lack of infrastructure	0	0	0	0	1	1	1	1	1	1	0	1	07
7	Technology immaturity	0	0	0	0	1	1	1	1	1	1	0	1	07
8	Lack of necessary technical skills and knowledge	0	0	0	0	1	1[a]	1	1	1	1	0	1	07
9	Integration of the grid with large scale renewable generation	0	0	0	0	1	1[a]	1[a]	1	1	1	0	1	07
10	Need of advanced bi-directional communication system	0	0	0	0	1	1[a]	1[a]	1[a]	1	1	0	1	07
11	Lack of open standards	1	1	0	1	1	1	1	1	1	1	1	1	11
12	Cyber security and data privacy	0	0	0	0	0	0	0	0	0	0	0	1	01
Dependence power→		05	05	01	03	11	10	10	10	10	10	02	12	**89/89**

[a] Incorporating transitivity.

Table 6
First Iteration for partitioning of levels of barriers to adopt Smart Grid technologies.

Barrier S. no.	Reachability set	Antecedent set	Intersection	Level
1	1,2,5,6,7,8,9,10,12	1,2,3,4,11	1,2	
2	1,2,5,6,7,8,9,10,12	1,2,3,4,11	1,2	
3	1,2,3,4,5,6,7,8,9,10,11,12	3	3	
4	1,2,4,5,6,7,8,9,10,12	3,4,11	4	
5	5,12	1,2,3,4,5,6,7,8,9,10,11	5	
6	5,6,7,8,9,10,12	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
7	5,6,7,8,9,10,12	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
8	5,6,7,8,9,10,12	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
9	5,6,7,8,9,10,12	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
10	5,6,7,8,9,10,12	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
11	1,2,4,5,6,7,8,9,10,11,12	3,11	11	
12	12	1,2,3,4,5,6,7,8,9,10,11,12	12	**1st**

The number of pair wise comparisons in the SSIM may be given by

$$((N)*(N-1)/2) \quad (1)$$

where N is the number of barriers

Therefore, number of pair wise comparisons $=12*11/2=66$

In this study, pair wise comparisons between identified twelve barriers have been made and total sixty six contextual relationships among the barriers to adopt smart grid technologies have been identified (Table 3).

3.2. Initial reachability matrix

The SSIM obtained in previous section is converted in to Initial Reachability Matrix by replacing four symbols (V, A, X and O) with binary digits (0 and 1) using following rules:

The (i, j) and (j, i) entry as 1 and 0 in the initial reachability matrix correspond to the (i, j) entry V in the SSIM; the (i, j) and (j, i) entry as 0 and 1 in the initial reachability matrix correspond to the (i, j) entry A in the SSIM; the (i, j) and the (j, i) entry as 1 and 1 in the initial reachability matrix correspond to the (i, j) entry X in the SSIM; and the (i, j) and the (j, i) entry as 0 and 0 in the initial reachability matrix correspond to the (i, j) entry O in the SSIM.

The development of initial reachability matrix for barriers to adopt smart grid technologies using above symbols has been explained as follows:

For V (1, 6) in SSIM, '1' has been given in cell (1, 6) and '0' in cell (6, 1) in initial reachability matrix; For A (2, 11) in SSIM, '0' has been given in cell (2, 11) and '1' in cell (11, 2) in initial reachability matrix; for X (7, 8) in SSIM, '1' has been given in cell (7, 8) and '1' in cell (8, 7) also in initial reachability matrix; and there is no O entry in SSIM in our developed SSIM.

An initial reachability matrix for the barriers to adopt smart grid technologies has been obtained as shown in Table 4.

3.3. Final reachability matrix

The initial reachability matrix is checked for transitivity rule to form final reachability matrix. The transitivity rule has been explained as: barrier 8 is related to barriers 5,7,9,10,12 and barrier 7 is related to 5, 6,8,9,10,12 in initial reachability matrix (Table 4). Barrier 8 is related to 7 and barrier 7 is related to barrier 6, then barrier 8 is necessarily related to barrier 6.

By adding transitivity to initial reachabilty matrix, the final reachabilty matrix has been obtained (Table 5). From the final reachabilty matrix, the driving power and the dependence power of each barrier have been calculated by adding all ones in the rows and all ones in the columns respectively. Final reachability matrix

for the barriers to adopt smart grid technologies has been shown in Table 5.

3.4. Partitioning of levels

The partitioning of levels has been done to obtain the importance level of each barrier to adopt smart grid technologies. The reachability and antecedent set for each barrier have been obtained from the final reachability matrix. The reachability set of a barrier is the number of barriers influencing it and the barrier itself. The antecedent set is consisting of the barrier itself and other barriers influencing it [53]. Reachability set, antecedent set and intersection sets for all the barriers have been identified from the final reachability matrix. Barrier having same reachability set and the intersection set is assigned as top level barrier in the ISM hierarchy or level 1 [48] and is shown in Table 6.

Barrier coming on level 1 is then discarded for the next iteration to find further levels. The developed ISM hierarchy illustrates positioning of variables at various levels is very significant and the lower level variables does not work significantly to get other variable lying on higher levels. Once one determines the top positioned element, soon it is omitted and process repeats till lowest position variable [54]. Second iteration for partitioning of levels of barriers to adopt smart grid adoption technologies has been shown in Table 7.

This iterative procedure is repeated till the importance level of each barrier is found (summarized in Table 8).

Table 7
Second iteration for partitioning of levels of barriers to adopt Smart Grid technologies.

Barrier S. no.	Reachability set	Antecedent set	Intersection	Level
1	1,2,5,6,7,8,9,10	1,2,3,4,11	1,2	
2	1,2,5,6,7,8,9,10	1,2,3,4,11	1,2	
3	1,2,3,4,5,6,7,8,9,10,11	3	3	
4	1,2,4,5,6,7,8,9,10	3,4,11	4	
5	5	1,2,3,4,5,6,7,8,9,10,11	5	**2nd**
6	5,6,7,8,9,10	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
7	5,6,7,8,9,10	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
8	5,6,7,8,9,10	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
9	5,6,7,8,9,10	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
10	5,6,7,8,9,10	1,2,3,4,6,7,8,9,10,11	6,7,8,9,10	
11	1,2,4,5,6,7,8,9,10,11	3,11	11	

Table 8
Various levels of barriers to adopt Smart Grid technologies.

S. no.	Level no.	Barrier to adopt smart grid technologies (Barrier S.N.)
1	1st	• Cyber security and data privacy (12)
2	2nd	• Lack of innovativeness in the industry (5)
3	3rd	• Lack of infrastructure (6) • Technology immaturity (7) • Lack of necessary technical skills and knowledge (8) • Integration of the grid with large scale renewable generation (9) • Need of advanced bi-directional communication system (10)
4	4th	• Huge amount of investment and lack of financial resources (1) • Market uncertainty (2)
5	5th	• Low public awareness and engagement (4)
6	6th	• Lack of open standards (11)
7	7th	• Lack of regulatory framework (3)

We identified seven levels of barriers to adopt smart grid technologies in ISM hierarchy. Here, it may be noted that barrier “Cyber Security and Data Privacy (12)” been identified as top level barrier, i.e., level 1. Moreover, for iteration-1, “Lack of Regulatory Framework (3)” has been found least dependence power and maximum driving power with same antecedent and the intersection sets, therefore, qualifies to hold last level i.e. bottom level barrier (7th level).

4. Ism based model formation for barriers to smart grid adoption

From the final reachability matrix (Table 5) and various levels to adopt smart grid technologies (Table 8), the structural model is generated by vertices and edges, called diagraph [55]. After removing these transitivities among the variables, the digraph is transformed into the ISM-based model. This preliminary model' does not consider transitivity relations between variables, therefore an ISM-based model is framed after partitioning their levels. “Lack of Regulatory Framework” forms the bottom level of model, whereas “Cyber Security and Data Privacy” forms the top level. ISM based hierarchical model for barriers to adopt smart grid technologies has been developed as shown in Fig. 1.

From the above Fig. 1, it may be inferred that, there is strong lack of regulatory framework to adopt smart grid technologies. Due to lack of regulatory policies and regulatory interference, there is lack of open standards and lack of public awareness towards adoption of smart grid technologies. From above said barriers, there is strong disbelief among the government bodies and stakeholders about the potential benefits of smart grid technologies, which is resulting in barriers like huge amount of investment and lack of financial resources and market uncertainty. Lack of resources and market uncertainty barriers leads to some additional barriers like lack of infrastructure, technology immaturity, lack of necessary technical skills and knowledge, integration of the grid with large scale renewable generation and requirement of advanced bi-directional communication systems. Above all said barriers are resulting lack of innovativeness in the industry to

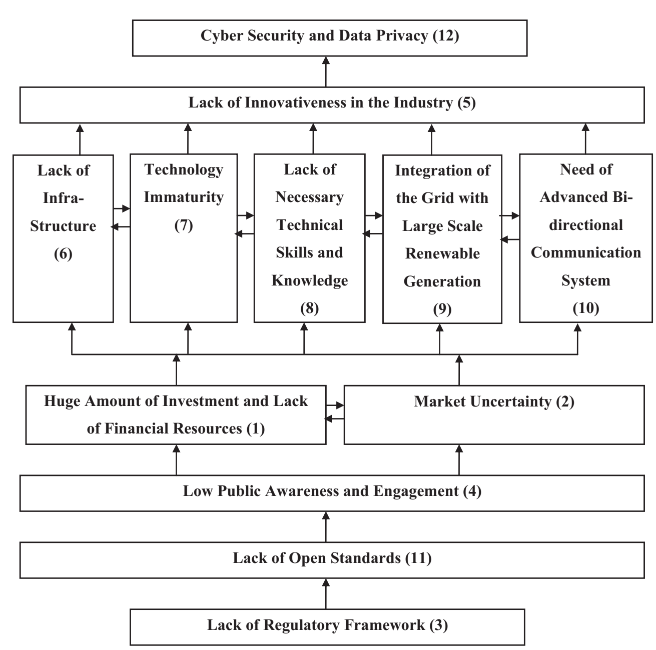

Fig. 1. ISM based hierarchical model for barriers to adopt smart grid technologies.

adopt smart grid technologies, which will further result in barrier like cyber security and data privacy.

5. Micmac analysis

The main aim of this section is to carry out analysis based upon driving power and dependence power of barriers (given in Fig. 2) and validation of developed ISM based model to adopt smart grid technologies. This analysis resulted in to classification of barriers in to four categories: autonomous barriers (having weak driving power and weak dependence power); dependent barriers (having weak driving power and strong dependence power); linkage barriers (having strong driving power and strong dependence power); and driver or independent barriers (having strong driving power and weak dependence power) to adopt smart grid adoption technologies [45,53,56]. Autonomous have few links, which may be very strong and may be discarded from the system. Dependent barriers have strongly dependent on other barriers. They will come at the top level in the ISM hierarchy. Linkage barriers are unstable in the fact that any action on these barriers will have an effect on others and also a feedback effect on themselves. They will come at the in between level in the ISM hierarchy. Barriers with a very strong driving power, called the 'key factor' falls into the category of independent or driver barriers. They will come at the bottom level in the ISM hierarchy.

In our study, there is no autonomous barrier. In our study, two barriers named "Cyber Security and Data Privacy (12)" and "Lack of Innovativeness in the Industry (5)" are lying in dependent barriers range and coming at top level of ISM based model. Five barriers named, "Lack of Infrastructure (6)", "Technology Immaturity (7)", "Lack of Necessary Technical Skills and Knowledge (8)", "Integration of the Grid with Large Scale Renewable Generation (9)" and "Need of Advanced Bi-directional Communication System (10)" are lying in linkage barriers range and coming middle of the ISM based model. Five barriers named "Lack of Regulatory Framework (3)", "Lack of Open Standards (11)", "Low Public Awareness and Engagement (4)", "Huge Amount of Investment and Lack of Financial Resources (1)" and "Market Uncertainty (2)" are lying in driver or independent barriers range and coming at bottom of ISM based model.

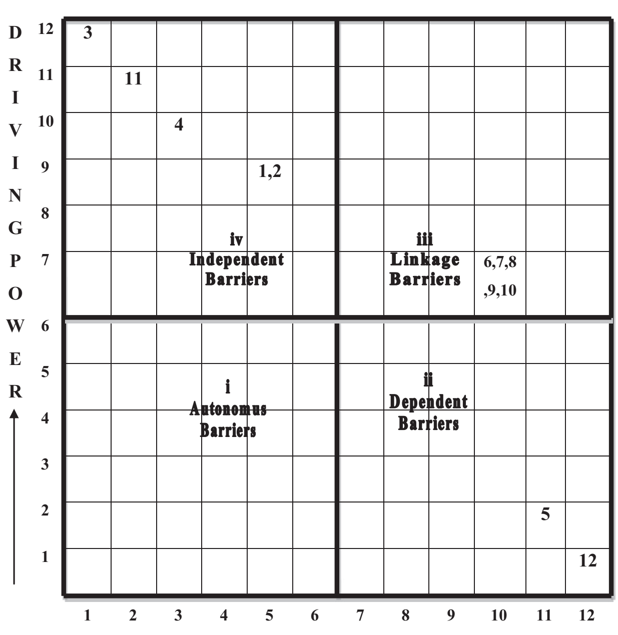

Fig. 2. MICMAC analysis for barriers to adopt smart technologies.

6. Disscusions

Increasingly growing electrical energy demand and reserves of conventional energy resources at the verge of depletion [51] may insist the human's race to rethink and analyze the energy 'demand and supply imbalance' scenario towards finding out sustainable and more efficient alternatives. Smart Grid is as an upgraded electricity network that enable two-way exchange of information and power between suppliers and consumers, with the help of intelligent communication monitoring and management systems [57]. Smart grid technologies adoption may play a significant role in achieving a fast, secure, safe, flexible, reliable, efficient, and environment friendly electrical systems [58]. But various regulatory, financial, market and technical obstacles hinder its rapid deployment and maturation [5]. Efforts are being done over the globe for adoption of smart grid and lot more has to be done for realizing the requirement and potential benefits of smart grid. However, to achieve this goal, a number of barriers will have to be overcome to adopt smart grid technologies.

ISM methodology has been utilized to identify interrelationships among these barriers. A hierarchical structural model using ISM methodology has also been presented for better understanding and removal of these barriers. Further, MICMAC analysis has been used to validate the ISM model based upon dependence and driving power of these barriers.

Smart grid technologies will result in creation of new jobs and possibly make the energy industry more attractive to a new generation of skilled workers throughout the energy supply chain, who are motivated to reduce carbon emissions and encourage energy efficiency [59].

6.1. Proposed solutions for managing barriers

Full estimation of the immaturity and uncertainty of smart grids is needed in order to speed up the process of smart grid deployment [30]. Strong regulatory framework, supportive government policies and international cooperation are required to overcome the barriers to implement smart grid adoption. Some proposed solutions have been suggested to deal with these barriers.

- Adequate regulatory framework at national and international platforms: there has been a general consensus that current regulatory framework may not capture completely the potential societal benefits of the smart grid technologies, and may act as a direct disincentive to energy efficient investment and innovation [59]. Regulatory framework should always create sufficient motivation for fostering the market at national and international platforms; and modifications are required in regulatory mechanism to encourage the utilities to invest in the smart grid technologies installations by giving incentives towards external and internal motivations for certain aspects of electricity sold and exchange of information on energy production between various stakeholders [23,33]. Regulatory bodies may create new supportive policies and regulations that remove economic and political barriers to integrated markets, while incentivizing capital investment [35].
- Setting up clear, common and open standards: first of all smart grid definition need to be universal. Governments, regulators, public and the private sectors should come forward joining hands to establish policies and standards encouraging interoperability and open architecture [60]. Efforts should be made at international platform by various bodies to create a common strategy in developing standards with industry and stakeholders participation, which will ensure the interoperability [61].
- Customer involvement and education: smart grid technologies adoption cannot be realized without active participation of

customers and very small fraction of the population know about smart grid technologies [62]. Government, universities and schools may take initiatives to make general people and students aware/educate about the smart grid technologies [1] and benefits from future electricity systems and markets. Consistent e-mailing and messaging at state, national and international levels are required to increase customer awareness and explain the benefits and changes associated with smart grids. Before placing customers on smart grids, they may be given sample bills to show how much they save [60]. To encourage rapid widespread of smart grid technologies adoption, the media may play an important role; and media should have special segment to focus more on smart grid technologies.

- Customer protection policy: smart grid utilizes digital technology, fostering it to be consumer friendly, practicable and duly protected from information security threats [43] such that customers have full faith and confidence in using new technology without any fear of misuse of on-line private data by hackers. Further, customers should be made aware of the new risks and threats of technology and ways to deal with it [63]. A set of approved and well-defined standards for security technologies may be found important towards successful and secure implementation of the smart grid technologies [64,65].
- Research and Development (R&D) Programs: systematic mechanism should be developed by the governments to provide rewards and incentives for the utilities and industries to invest in research, development and demonstration [60]. Strong, targeted and globally joint R & D work, in the area of advanced metering and real-time pricing supported by customers' feedback [66], should be started to fully enjoy its potential benefits.
- Advanced bi-directional communication systems: advanced bi-directional communication systems for the flow of energy and information between the networks and end-use devices are the back bone of smart grid. Without advanced communications systems, the essential enabling components of the future smart grid communications architecture like, smart metering communications, can't be realized [21]. Full potential of smart grid technologies may only be realized by making pre programmable, seamless and automatic connection between the network and end-use devices, leading to emphasis upon more R&D work on compilation and reviewing of existing automation technologies; and identification of best practices [60].
- Development of infrastructure: additional infrastructure should be added to existing grids to set up advanced bi-directional communications systems. Additional actuators and sensors should be incorporated for improved controllability of the distribution systems [33]. Additional infrastructure is also required for integration of the grid with large scale renewable generation systems. To increase the capacity and also reduce the emission of GHG, more and more renewable generation systems should be integrated with current electrical system [49]. Various international and national bodies lead to assign appropriate budget for the development of infrastructure for smart grid technologies.
- Technical training programs: being smart grid relatively new technological area, appropriate training programs needs to be structured to meet the requirement of skilled workforce [36]. To address this, the government and private bodies may examine the skills needed and how they can be developed across the industry [59]. Separate course work/specialization in engineering programs may be designed for smart grid technology in government and private engineering colleges.
- Social responsibility: smart grid technologies should be considered as a possible solution to recent operational and societal challenges; and may address new needs resulting in to positive benefits, return in the long run, reduction in global warming, since it is a good example of green technology which is helpful in reducing global warming [67]. However, compared with other technologies, green technology might take a longer time to produce economic benefits; its adoption is often motivated more by non-monetary benefits such as corporate social responsibility, rather than financial incentives [29,68].

6.2. Implications of the research

Smart grid technologies adoption is requirement of today's scenario to achieve uninterrupted power supply in sustainable way. Unfortunately, implementation of smart grid technologies is not very successful due to some barriers.

- Policy makers may face lots of challenges in identifying these barriers and then working upon them to improve the smart grid technologies adoption. In this paper, an attempt has been made to identify and analyze potential barriers to successful adoption of smart grid technologies through extensive literature review and experts' opinions.
- Identification of barriers to adopt smart grid technologies will help practitioners in removal of barriers. We have also included a section named "proposed solutions for managing barriers", which will be also beneficial for practitioners/energy supply chain managers in removal of barriers.
- Structural self-interaction matrix will help to understand regulators/policy makers/governments for better understanding of identified barriers' interactions and interrelationships.

Cyber Security and Data Privacy and Lack of Innovativeness in the Industry have been identified as dependent barriers. Lack of Infrastructure, Technology Immaturity, Lack of Necessary Technical Skills and Knowledge, Integration of the Grid with Large Scale Renewable Generation and Need of Advanced Bi-directional Communication System have been identified as linkage variables. Lack of Regulatory Framework, Lack of Open Standards, Low Public Awareness and Engagement, Huge Amount of Investment and Lack of Financial Resources and Market Uncertainty has been identified as independent barriers. Lack of Regulatory Framework barrier has been found bottom most level in developed ISM based hierarchy model and identified as most powerful barriers; and removal of this barrier may help in removing maximum number of other barriers. So, it is suggested that Lack of Regulatory Framework barrier needs to be removed before removal of other barriers. The results of this study may help policy makers and energy supply chain managers in efficient decisions making directing future efforts in implementation of smart grid technologies.

7. Conclusions

Strong need has been felt to understand, analyze feasibility and requisite of smart grid technologies adoption around the globe. In this direction, we have dealt with twelve barriers to adopt smart grid technologies, identified literature review and experts' opinions. An attempt has been made to critically examine these barriers hindering adoption of smart grid technologies and further, analyze pair wise interactions among these barriers. ISM methodology and MICMAC analysis have been utilized for modeling of the barriers and subsequent validation of the model so developed. Seven levels have been identified in the ISM based hierarchy model. "Lack of Regulatory Framework" barrier is coming at the bottom of the structural model and "Cyber Security and Data Privacy" barrier is coming at top of the structural model. No autonomous barrier, two dependent barriers, five linkage barriers and five independent barriers have been identified in MICMAC analysis. By putting continuous efforts towards managing

independent driver barriers, other barriers may be worked upon and will play an important role in adoption of smart grid technologies.

Strong need has also been felt to towards motivation of R&D and innovative activities implementation; adequate infrastructure development and carrying out knowledge management and technology transfer in most effective manner in the field of smart grid technologies adoption. We recommend having efficient and more advanced communication systems after analyzing their cost implications and practical difficulties in implementation. Keeping in view, growing concern about economic, environmental and social consequences; and rapidly increasing energy demands, strong motivation is required for carrying out research towards renewable energies adoption and integration with smart grid technologies.

7.1. Limitations of the study

Every research has its own limitations. ISM based hierarchical model of barriers to adopt smart grid technologies has been developed and following limitations have been reported:

- The developed model is highly judgmental based upon experts' opinions.
- In order to develop SSIM in ISM procedure, establishing the contextual relationships by consulting with experts may find it a tiring task since it demands significant concentration and time. Therefore, idea engineering workshop was conducted for finding contextual relationships among identified barriers and experts are not randomly selected.
- Further, barriers needs to be quantified, which has not been considered in the scope of this paper.

7.2. Scope of future research

Present research work is based on the literature review, ISM methodology and MICMAC analysis. The following are some research directions suggested for future research based on this work:

- Statistical validation may be carried out of the data collected from the questionnaire based survey concentrating upon specific country scenario supported by case studies.
- Further, Structural Equation Modeling (SEM) or Systems Dynamics Modeling (SDM) may be used to test the validity of the suggested model.
- Quantification of these barriers and their interrelationships may be done by carefully adopting graph theory, Analytical Hierarchy Process (AHP), Analytical Network Process (ANP) and Technique for Order Preferences by Similarity to Ideal Solution (TOPSIS) etc.
- The ISM and MICMAC considers only binary type of relationships, where as in fuzzy MICMAC an additional input of possibility of interaction between the elements is introduced. By introducing fuzzy set theory, the sensitivity of conventional MICMAC analysis can be increased.

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